Development of a Unified Criterion for Solar Collector Selection

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To assist in making engineering or management decisions, this article explores the possibility of building a single selection criterion to distinguish between different solar collector subsystems for a specific application or between different complete solar-powered systems. The development of two analogous criteria are discussed. The criteria combines both performance and unit area costs, and presents the dollar per unit power and the dollar per unit energy produced from a solar plant. Typical values for current focusing and nonfocusing solar collectors were included to support the discussion. The first phase development shows that the criteria evaluation is in need of more data about the annual dynamic behavior of the collector subsystem only, under the transient site-specific parameters such as solar flux, wind, and ambient temperature.

I. Introduction

It is a fact that the last decade has witnessed a great deal of research and development in nonfossil fuel energy sources to find a solution to the energy shortage problem. Many industrial organizations, academic institutes and research laboratories including the Jet Propulsion Laboratory, have started energy research and conservation programs. Solar energy as one of the nondepletable sources has been under thorough investigation, and the solar collector component, as an entity, has occupied a major part of that investigation.

The above competitive efforts blossomed many collector concepts. Some concepts are still on paper while others are ahead in production phase. No bounds or standards are set to unify the parameters of module geometry, physical dimensions, weight, operating temperatures, optical properties of coatings or glazing, insulation thicknesses, heat loss rates, etc. Consequently, large collections of information and data regarding performance and cost of many "good" solar collectors were established. The differences in cost and performance are wide not only between collectors of different categories but also between collectors of the same category. Collector manufacturers enlarge this difference gap and support their own product selection rationale to obtain either high performance using expensive high grade materials or to sacrifice performance for a low cost product.

For a given application, the selection of the solar collector, whether it is a focusing or a nonfocusing type, affects the overall installation, operation and maintenance cost. For engineering or management decisions, the question that eventually will rise is which collector possesses the "best" score? The comparative adjective "best" means in engineering terms the one that not only scores highest in fulfilling its purpose at the required operating conditions with the least cost but also scores highest in reliability, durability, low risk, nonhazardous and low maintenance problems. Any cost methodology such as a life cycle cost analysis, a cost/benefit payback period analysis, or a cash flow analysis, may be used to support the selection rationale.

In the present article, the development of a single collector criterion combining performance and unit cost is explored to be used as a figure of merit. The other operational parameters of risk, maintenance, and reliability are not included for two reasons: (1) there is not enough data accumulated about collector failures, maintenance and durability to judge a newly developed solar collector, and (2) reliability and maintenance figures of merit using the probability theory are addressed elsewhere in detail and could be added to the total selection of analysis once a cost/performance criterion is established.

The main objectives of this study are set to (1) provide a means to distinguish between different solar collectors or integrated solar-powered systems for a given application combining only performance and unit cost, (2) reduce or eliminate the need for costly site-specific experimental tests once a good performance model is established at another site with different weather spectrum and (3) assist engineering and/or management in making decisions in system evaluation and cost effectiveness.

II. Collectors for Electric Power Generation

In comparing focusing collectors (such as parabolic troughs, parabolic dishes, fresnel lenses, etc.) with nonfocusing types (such as flatplate collectors) for electric power generation, the points in favor and against each type are as follows:

(1) Focusing collectors tend to have, in general, higher collection efficiency than nonfocusing types. This is caused by the reduction in heat losses as a result of small concentration areas which is much less than the increase in heat losses caused by high temperatures attained.

(2) Nonfocusing collectors have the ability to harness the diffuse radiation while focusing types do not have. Diffuse radiation can be as much as 20% of the total incident flux on clear days. This ratio goes up on cloudy days. On the other hand, nonfocusing collectors are generally nontracking and the radiation cosine losses due to their fixed oblique orientation (cosine the angle of incidence) exceeds the gain of the extra diffuse part. The result is a less peak and accumulated radiation intensity for clear days than tracking focusing collectors. The situation is reversed on cloudy days. However, it appears that this extra diffuse part plays an insignificant role in collection efficiency increase since nonfocusing collectors have generally higher efficiency as stated in item (1).

(3) Although tracking in focusing collectors is essential and adds an extra cost to the power plant, it is desirable in maintaining a constant collector efficiency for longer periods over the day. This is in contrast with nontracking nonfocusing types that possess an undesirable steep rate of efficiency decrease with operating temperature.

The above points indicate that collectors with high performance are accompanied by high cost and vice versa. The need for a selection methodology then follows as an essential tool for comparison of the various types.

The cost of a solar-electric power plant is greatly influenced by the overall conversion from solar-to-electric efficiency. If conversion is done via thermal power cycles, the efficiency is simply the product of collection efficiency times the power cycle thermal efficiency as shown in Fig. 1.

The efficiency trends shown in Fig. 1 for both the collector and the power cycle are general for any type of each. The collection efficiency always decreases with increasing operating temperature due to higher thermal losses and can reach zero when the incident radiation equals the losses at point B. The power cycle efficiency, on the other hand, increases with the operating temperature and starts from zero at ambient temperature, point A. The overall conversion efficiency will be zero at both points A and B and always possesses a maximum value in between A and B. The optimum operating temperature corresponding to maximum overall conversion efficiency should be the system design point.

III. Derivation of Maximum Solar/Electric Conversion Efficiency

The performance of solar collectors is generally the same whether they are focusing or nonfocusing types. The instantaneous collector efficiency (E_c) can be expressed approximately by the linear form

$$E_c = a_1 - b_1 \left(\frac{T - T_0}{I} \right) \tag{1}$$

where

I = solar intensity per unit collector area

T_0 = ambient temperature

a_1 = collector constant representing its optical efficiency

b_1 = collector constant representing its thermal loss coefficient

T = Plate (receiver) temperature of the collector

Equation (1) can be put in the compact linear form:

$$E_c = a_2 - b_2 T \tag{2}$$

where a_2 and b_2 are collector constants given by

$$\left.\begin{aligned} a_2 &= a_1 + b_1 \frac{T_0}{I} \\ b_2 &= \frac{b_1}{I} \end{aligned}\right\} \tag{3}$$

The constants a_2, b_2 are considered collector "characteristic" constants to differentiate between shapes, geometry, optical and thermal properties for a given ambient temperature and solar intensity.

On the other hand, the thermal efficiency of power cycles can be expressed in general as a fraction of the corresponding Carnot's cycle working between the same source/sink temperature limits. This fraction is a function of many conditions, such as type of cycle, type of working fluid, pressure and temperature ranges, etc.

The ratio (λ) of real power cycle efficiency to Carnot's working between the same temperature limits, ranges in practice from 0.4 to 0.6 at full load. Accordingly, the thermal efficiency of a real power cycle working between a hot surface temperature T and an ambient temperature T_0 is approximated by

$$E_e = \lambda \left(1 - \frac{T_0}{T}\right) \tag{4}$$

The overall conversion from solar to electric efficiency (E_0) then follows as

$$E_0 = E_c \times E_e$$

or by combining Eqs. (2) and (4)

$$E_0 = \lambda \; (a_2 - b_2 T) \; \left(1 - \frac{T_0}{T}\right) \tag{5}$$

The overall conversion efficiency from Eq. (5) can be zero at two positions:

(1) Where the collector efficiency is zero at a maximum temperature:

$$T_B = \frac{a_2}{b_2} \qquad \text{(point B on Fig. 1)}$$

(2) At a temperature $T_A = T_0$, or when the engine efficiency is zero at ambient temperature (point A on Fig. 1).

Assuming that the parameters a_2, b_2, and λ are unchanged with the collector temperature, the overall conversion efficiency will possess a maximum value $E_{0,max}$ at the optimum temperature T_{opt} given by differentiation as

$$T_{opt} = \sqrt{a_2 \, T_0 / b_2} \tag{6}$$

$$E_{0,max} = \lambda \, a_2 \left(1 - \frac{T_0}{T_{opt}}\right)^2 \tag{7}$$

Equations (5) and (7) show that at the optimum operating temperature

$$E_c = \frac{a_2}{\lambda} \cdot E_e \tag{8}$$

This means that if the value of (a_2) is equal to (λ) the optimum temperature (T_{opt}) will be the intersection point between the engine efficiency and collector efficiency curves. The location of the optimum temperature will be lower than the intersection temperature or higher depending on whether the value of (a_2/λ) is larger or smaller than 1, respectively.

The optimum operating temperature for the combined collector-engine system as calculated from Eq. (6) is dependent on the slope (b_2) and ordinate intersection (a_2) of the collector efficiency line. Smaller slopes and larger ordinate intersection produce higher overall conversion efficiency $E_{0,\max}$ and higher optimum temperature. This explains why focusing collectors are offering a superior performance compared to nonfocusing types.

IV. First Selection Criterion for Solar-Electric Plant ($/kWe)

From an engineering viewpoint, a solar-electric plant should be combining good performance (presented by the maximum overall conversion efficiency) and low cost to compete with conventional fossil-fuel or nuclear power plants. Before rating different collectors or different energy conversion systems, the following parameters and assumptions will be fixed for all candidates under investigation:

(1) Operating temperature will be the optimum value corresponding to the maximum overall conversion efficiency.

(2) Site and location with its topography and geography is the same to each candidate.

(3) Weather spectrum, ambient temperature, humidity, wind speed, and direction are the same to each candidate.

(4) Cloud cover, thickness, height, dispersion, and frequency of appearance are the same to each candidate.

(5) Clear day solar insolation spectrum is the same for all candidates. Even though focusing and nonfocusing collectors receive different proportions of direct, diffuse, and ground reflected parts, the conversion efficiency is assumed to be independent of the intensity of input energy. In other words, each collector will be scored and judged according to its ability to collect and transfer to the working fluid the solar energy which was harnessed.

(6) Maintenance and operation costs (M&O) will be assumed in direct proportionality to the unit collector cost ($/m^2). This means that expensive collectors will have larger M&O costs than inexpensive ones. These annual costs will constitute a fixed percentage (of order 10% for example) of the installation cost.

The collection surface area can be calculated from the simple equation:

$$\text{collector area (m}^2\text{)} = \frac{\text{electric power output (kWe)}}{\text{solar radiation intensity (kWt/m}^2\text{)} \times \text{overall solar-electric conversion efficiency } (E_{0,\max})} \tag{9}$$

The electric power output in the numerator and the solar radiation intensity in the denominator should be computed during the same time interval. The latter could be a 15-min peak, a daily average, a monthly average, a seasonal average or a yearly average. The overall solar-electric conversion efficiency is determined by using Eq. (7), with fixed solar radiation and ambient conditions.

The installation cost in dollars of the whole solar power plant including energy collection, conversion, storage, and transport subsystems can be divided by the total collection area (in m^2) to yield a unit installation cost in ($/m^2). The operation and maintenance cost when added as a fixed percentage of the installation cost will facilitate the comparison, so that we need only to speak about the unit plant cost.

The total plant (or collector) cost per kW_e output can thus be given by:

$$\text{plant (or collector) \$/kWe} = \frac{\text{unit plant (or collector) cost (\$/m}^2\text{)}}{\text{solar radiation intensity (kWt/m}^2\text{)} \times \text{overall solar-electric conversion efficiency } (E_{0,\max})} \tag{10}$$

Equation (10) applies to any solar-electric plant whether it is an indirect thermal-electric conversion via power cycles or a direct solar-electric conversion such as photovoltaic cells. Also, Eq. (10) can be used in comparing collectors only for solar-electric application by using the unit collector cost $/m^2 instead of the unit plant cost ($/m^2).

A common reference value of the solar radiation intensity is one "sun" defined as a peak intensity of 1 kWt/m^2 (0.1 W/cm^2 or 317 Btu/h ft^2) at solar noon. For tracking collectors, the intensity of 1 kWt/m^2 is considered a suitable incident radiation reference. But for nontracking collectors, a radiation reference of 0.8 kWt/m^2 will be chosen as a radiation reference to account for the cosine of the angle of incidence losses. Under these radiation references, the cost of any solar-electric plant (or collector) per electric kilowatt at the bus bar can be given by substituting in Equation (10). For solar-electric power plants with tracking solar collectors,

$$\text{total plant (or collector cost) \$/kWe} = \frac{\text{unit plant (or collector) cost \$/m}^2}{\text{overall conversion efficiency } (E_{0,\max})} \tag{11a}$$

For solar-electric power plants with nontracking solar collectors,

$$\text{total plant (or collector) cost \$/kWe} = \frac{\text{unit plant (or collector) cost \$/m}^2}{0.8 \times \text{overall conversion efficiency } (E_{0,\max})} \tag{11b}$$

Equations (11a, b) present the first figure of merit (\$/kWe) which differentiates between the different solar-electric conversion systems combining both performance and cost. Other figures of merit representing maintainability, risk, durability, etc., can be added to complete the selection criteria.

Table 1 lists typical results for some current solar collectors. The instantaneous efficiency curves are plotted as shown in Fig. 2 versus the average collector temperature. The heat engine efficiency working at 50% of Carnot's between the collector temperature and ambient temperature 25°C (77°F) is also plotted for reference. Some cost and efficiency data were abstracted from Refs. 1 through 12.

Equations (6) and (7) are used to calculate the optimum operating temperature and the maximum overall conversion efficiency, respectively. The unit collector cost ($\$/m^2$) figures were either abstracted from manufacturer data or estimated from past experience. Equations (11a, b) are used to estimate the \$/kWe figures as given in Table 1. The maximum overall conversion efficiencies were in good agreement with some of the values reported in Refs. 13 and 14 using other derivations.

It is apparent from Table 1 that focusing collectors with their high temperature capability, in spite of their high cost, are favored for solar-electric conversion. However, the rate of decreasing costs by mass production in focusing and nonfocusing types can change the selection procedure. Table 2 for example, shows how the competition between solar collectors can be tough. The three hypothetical solar collectors presented in Table 2 have different optimum performance figures as presented by 3%, 8%, and 16% conversion efficiency and different unit cost as given by \$60, \$200, and $\$400/m^2$. According to Eq. (11), the collector cost alone per kWe output is the same for all of them and equals \$2500/kWe which appears to make the selection process not decisive. The first collector could be a typical flat plate collector as evidenced in Table 1. Also, the second collector could be a low performance parabolic trough, and the third collector could be a paraboloid, dish or a heliostat power tower collector. Furthermore, if the rest of the subsystems such as energy transport, conversion, and storage subsystems, excluding the collector subsystem, cost the same when producing 1 kWe, then the choice will still be narrowed down to that collector which requires the least land area for the given output. Table 2 shows that collection areas range from 6 to 42 m^2/kWe for the above cases depending on the overall conversion efficiency as given in Eq. (9). This collection area should further allow for shadowing effects, module spacing, etc., which means larger land areas and more installation cost. For these nondecisive cases, knowledge of collector performance over longer periods of time is very important, which leads to the second analogous criterion in the next section.

V. Second Selection Criterion for Solar-Electric Plants (\$/kWhe)

The unit plant (or collector) cost in \$/kWe derived in the last section cannot stand alone as the sole criterion for comparing different types of collectors. The "\$/kWe" figure has been derived based on "instantaneous" collector efficiencies measured at noon time with a fixed value of solar insolation and assuming a quasi-steady-state operation (1 kWt/m^2 for tracking collectors or 0.8 kWt/m^2 for nontracking types). In practice, solar collectors do not actually operate at their steady-state conditions since they are subject to many site-specific time varying variables such as solar flux, ambient temperatures and wind speed.

A collector response time, defined as the time taken to reach 99% of its steady-state temperature under a step change of the solar flux, is known to vary from a few minutes to about one hour according to the collector thermal capacitance. It appears, therefore, that a criterion based on a performance measure integrated (or accumulated) over a day, a month, or a year period would be more suitable in comparing different solar-electric power plants encompassing these transient conditions. The unit energy cost (\$/kWhe) produced by a solar-electric plant with performance integrated over one year could act as a second selection criterion to represent the effects of the dynamic and site-specific performance. The derivation of this criterion can be simplified as follows:

Let the annual electrical energy generated from a solar-electric power plant (W^*) in kWhe be given by

$$W^* = I^* \times A_c \times E_c^* \times E_e^* \times E_s^* \times E_T^* \tag{12a}$$

or

$$W^* = I \times A_c \times E_0^* \tag{12b}$$

where

I^* = accumulated annual solar flux, kWht/year

A_c = collectors area, m^2

E_c^* = accumulated annual collection efficiency

E_e^* = annual engine efficiency

E_s^* = annual storage subsystem efficiency

E_T^* = annual energy transport subsystem efficiency

E_0^* = annual overall solar-electric efficiency

The annual cost (C) in dollars could be calculated using the cost recovery factor (CRF) of the borrowed money in a lifetime mortgage plan as

$$\text{annual cost } (C) = \begin{bmatrix} \text{collector subsystem cost} \\ + \text{ storage subsystem cost} \\ + \text{ energy conservation subsystem cost} \\ + \text{ energy transport subsystem cost} \end{bmatrix} \times \left[\text{cost recovery factor } (CRF) \right] + \text{annual maintenance and operation cost} \tag{13}$$

In most applications, the energy storage, transport, and conversion subsystems cost will be assumed to be a fixed fraction of the collector subsystem cost. Also, the annual maintenance and operation cost will be assumed in proportion to the total installation cost. Consequently, Eq. (13) could be rewritten as

$$C \simeq A_c \times C_c \times R \tag{14}$$

where C_c is the collector cost per unit area (\$/m^2), and R is the ratio of the total annual cost to the total collector cost. For example, if the collectors lifetime is taken as 20 years and the interest rate on the borrowed money is 8%, the (CRF) will be 0.10185 \$/yr With approximately a 4:1 ratio between total installation to collector cost, the ratio R is found to be around 0.4.

The cost per unit electrical energy output then follows by combining Eqs. (12b) and (14) as

$$\text{cost/kWhe} = \frac{C}{W^*} = \frac{C_c \cdot R}{I^* \cdot E_0^*} \tag{15}$$

For example, if a paraboloid solar collector is built with 450 \$/m^2, a ratio of R of 0.4, an annual overall solar-electric conversion of 0.18, and an accumulated annual insolation of 3126 kWht/m^2 (a daily average direct normal flux of 8.7576 kWht/m^2 such as that measured at Goldstone area, California) the cost per kWhe produced would be approximately 0.31 dollars.

The cost/kWhe criterion expressed mathematically in Eq. (15) indicates that in order to generate low cost electrical energy, the parameters, C_c, R, I^* and E_0^* should be in harmony with each other and not separately optimized. For instance, if a flat plate collector, having a unit cost of 60 \$/m^2, an annual conversion efficiency of 0.03 and an annual solar flux of 2604 kWht/m^2, is compared with the above paraboloid dish example with the same ratio of R of 0.4, the cost of energy produced would be 0.307 dollars/kWhe which is approximately the same for both types. The first collector (paraboloid dish) has a high unit cost (C_c), receives high solar flux as a result of tracking, and has a high conversion efficiency because of its high operation temperature. The second collector is completely opposite to the first, but both produce energy with the same cost. The final selection in this case should be guided by other factors such as durability, maintainability, land areas, visibility etc.

The second criterion shows clearly the important need of accurate site-specific transient analyses to predict the annual conversion efficiency (E_0^*) of different solar-electric systems to support the first criterion which is not site-specific.

VI. Solar-Cooling Application

To use the solar energy as a driving force for cooling devices, several well-known concepts can be coupled with a heat source. Shown in Fig. 3 are the coefficient of performance trends versus the collection fluid temperature leaving the collector subsystem for some of the above concepts. Superimposed on Fig. 3 is the general behavior of the collector efficiency. The overall coefficient of performance (*OCOP*) is defined as the ratio between the refrigeration effect (Q_3) and the incident solar flux (Q_1) as illustrated in Fig. 3. Thus

$$OCOP = \frac{Q_3}{Q_1} = \frac{Q_3}{Q_2} \times \frac{Q_2}{Q_1} \tag{16}$$

or

$$\begin{bmatrix} OCOP \end{bmatrix} = \begin{bmatrix} \text{collector} \\ \text{subsystem} \\ \text{efficiency} \end{bmatrix} \times \begin{bmatrix} \text{cooling} \\ \text{subsystem} \\ COP \end{bmatrix} \tag{17}$$

The overall system performance possesses always a maximum value at an optimum temperature in between the ambient temperature (A) (where the coefficient of performance of the cooling subsystem is zero) and the equilibrium collector temperature (B) (where the collector thermal losses are equal to the incident solar flux). The point of maximum *OCOP* should be the selected design point, and is usually determined by curve plotting instead of analytical expressions.

Similar to the discussion presented in Section IV, the unit power cost (\$/kWe) for solar-electric application will be replaced here by the unit power cost (\$/Tons of refrigeration[1]) for solar-cooling devices. The overall solar-electric conversion efficiency (E_0, max) will also be replaced by the overall-solar-cooling effect coefficient of performance $(OCOP)_{max}$. All other parameters bear the same meaning.

The first criterion, presented in Equations (11a, b) for solar-electric conversion, could be rewritten then for solar-driven refrigeration devices as follows:

[1]One ton of refrigeration = 12000 Btu/h = 3.516 kWt cooling energy.

For tracking solar collectors (intensity = 1 kWt/m^2):

$$\begin{array}{l}\text{total plant}\\ \text{(collector)}\\ \text{cost \$/Ton}\end{array} = 3.516 \times \frac{\text{unit plant (or collector) cost \$/m}^2}{\begin{bmatrix}\text{overall coefficient of performance} \\ (OCOP)_{max} \text{ from} \\ \text{solar-refrigeration effect}\end{bmatrix}} \tag{18a}$$

For nontracking solar collectors (at intensity of 0.8 kWt/m^2)

$$\begin{array}{l}\text{total plant}\\ \text{(collector)}\\ \text{cost \$/Ton}\end{array} = 4.4 \times \frac{\text{unit plant (or collector) cost \$/m}^2}{\begin{bmatrix}\text{overall coefficient of performance} \\ (OCOP)_{max} \text{ from} \\ \text{solar-refrigeration effect}\end{bmatrix}} \tag{18b}$$

Also, for the second criterion, the cost per unit "cooling" energy or \$/(Ton·h) could be derived by the same procedure used for solar-electric plants. Analogous to Eq. 15, the (\$/Ton·h) could be written as:

$$\text{cost/(Ton} \cdot \text{h)} = \frac{3.516 \cdot C_c \cdot R}{I^* \cdot (OCOP)^*} \tag{19}$$

where $(OCOP)^*$ is the accumulated annual overall coefficient of performance (from solar flux-to-refrigeration effect). All the other parameters bear the same meaning as before. Again, the transient response to the fluctuating solar flux, ambient conditions and wind speed, etc., are very necessary in order to estimate the annual performance before comparing different refrigeration schemes.

VII. Solar-Heating Application

For this particular application, the first criterion does not apply and only the second one does. The estimated unit cost of thermal energy collected (\$/kWht) is the key number needed for comparison with other conventional heating devices such as fuel-fired boilers, electric heaters, or heat pumps. Analogous to Eq. (15), the (\$/kWht) is written for solar heating as

$$\text{unit energy cost \$/kwht} = \frac{C_c \cdot R}{I^* \cdot E_H^*} \tag{20}$$

where E_H^* is the combined annual efficiency of the collectors and storage subsystems. All other parameters bear the same meaning as used before. Only in solar heating applications, the value of the operating fluid temperature has to be specified in advance before calculating E_H^*. For example, if the solar heating application is for space heating then the E_H^* would be estimated with the candidate collectors producing a uniform temperature of 49°C (120°F), which is enough for this application. For domestic hot water use, a temperature ranging from 60 to 82°C (140 to 180°F) is adequate, and shall be used for estimating E_H^*. This means that the evaluation of E_H^* is assumed to be done at a single value of collector temperature, for all competing collectors, irrespective of the possible ranges of higher temperature beyond this value that each collector can reach. Therefore, each collector will be judged on how much annual energy was collected from the sun and transferred to the end point at a prespecified heating temperature. Once more, for heating application, the collectors transient behavior and their sensitivity to time-varying input data, is of great value to any comparison process.

VIII. Summary

The following points summarize the present study:

(1) To make a good engineering or management decision as to which collector or solar-conversion device should be used in a given solar application, two analogous selection criteria are presented. The first criterion gives the unit cost per unit power produced, based on instantaneous solar radiation or noon-time flux. The (\$/kWe) for solar-electric application and the (\$/Ton) for solar-refrigeration devices, are two examples of the first criterion. The second criterion gives the unit cost per unit energy accumulated (or integrated) over a year period and taking into consideration the fluctuating nature of the solar flux, ambient temperature, wind speed and the thermal capacitance of the collector itself. The (\$/kWhe) for solar-electric conversion, the (\$/Ton·h) for solar-refrigeration conversion and the (\$/kWht) for solar-heating are examples of the second criterion.

(2) The first criterion was tested for solar-thermal-electric conversion and for 13 types of available collectors (Table 1). The (\$/kWe) figure was found lowest among tracking and focusing collectors and highest among flat-plate, nonfocusing, nontracking collectors. However, the need for transient performance data for the second criterion (\$/kWhe) is found very essential before a final selection process can be made.

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Table 1. Typical results for some current collectors[a]

No.	Collector	Tracking	$E_{0,max}$, %[a]	Collector, \$/m^2	Collector, \$/kWe	Optimum temperature, °C(°F)
1.	Owens-Illinois (Refs. 1 and 5)	No	3.50	200	7137	135 (275)
2.	Winston (compound parabolic) (Refs. 2 and 3)	No	3.93	140	4450	133 (271)
3.	Croning (tubular evaculated) (Ref. 4)	No	9.96	140	1763	191 (376)
4.	Parabolic trough (Refs. 6, 7, and 8)	Yes	11.9–12.7	175	1380–1470	316–430 (600–805)
5.	Northrup collector (Fresnel lens) (Ref. 9) (Corning tube tested)	Yes	13.3	135–240	1020–1810	433 (812)
6.	Northrup collector (black paint) (Ref. 9)	Yes	5.8	135	2340	123 (253)
7.	Parabolic dish (or power tower) Ref. 10)	Yes	18–28	250–450	800–2500	1400 (2560)
8.	NASA-Honeywell, black nickel (Ref. 5) 2 Ar-double glazing (flat plate)	No	5.21	170	4125	108 (227)
9.	NASA-Honeywell, black nickel (Ref. 5) Double glazing (flat plate)	No	4.4	100	2812	111 (231)
10.	Double glazing (general collector) Flat plate, nonselective	No	3.12	100	4000	92 (197)
11.	Liquid lens concentrator (Ref. 11)	Yes	12.2	150	1220	358 (676)
12.	Sheldal (slats) fixed receiver, tracking reflector (Ref. 12)	Yes	13.7	180	1310	428 (803)
13.	General Atomics fixed mirror receiver	Yes	11.9	160	1340	431 (808)

[a] At 25°C ambient temperature.

Table 2. Comparison between three hypothetical collectors

Parameter	Collector (type 1) flatplate	Collector (type 2) parabolic trough	Collector (type 3) paraboliod dish
$E_{0,max}$, %	3	8	16
Collector cost \$/m^2	60	200	400
Reference intensity, kwt/m^2	0.8	1.0	1.0
Power collected cost \$/kWe	2500	2500	2500
Surface area m^2/kWe	41.6	12.5	6.2

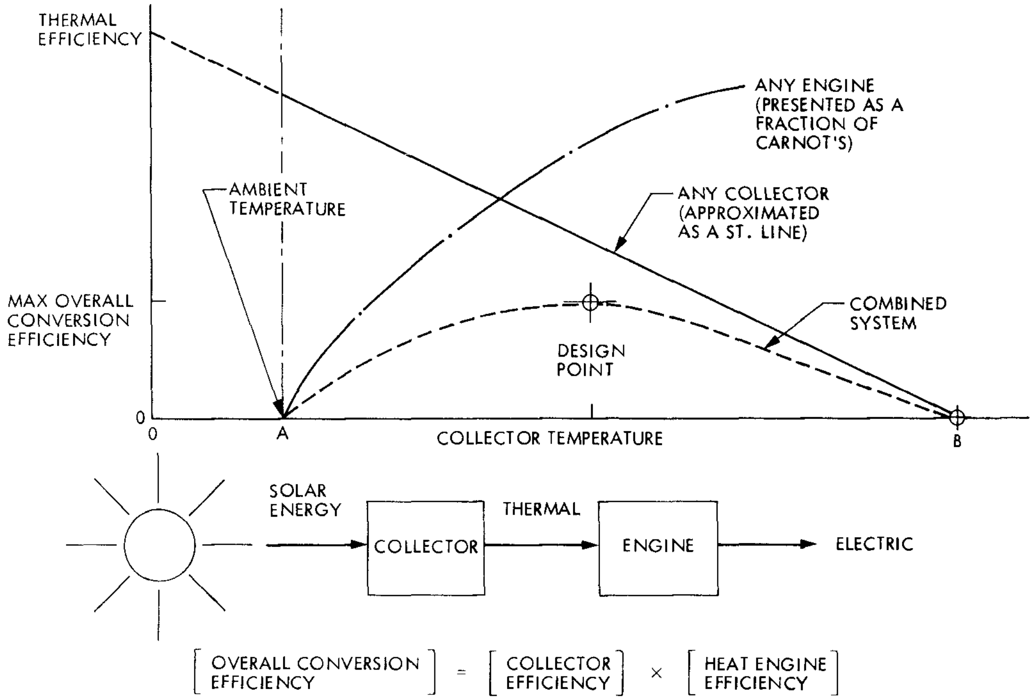

Fig. 1. Optimization of solar thermal-electric conversion

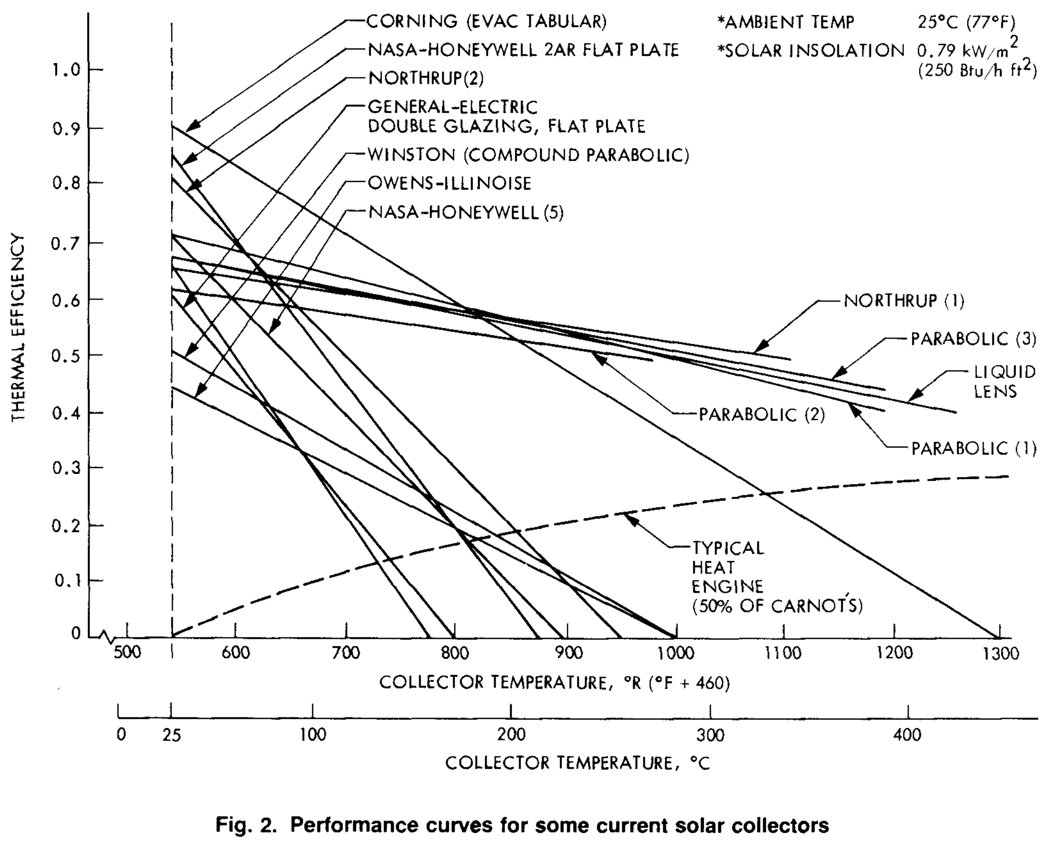

Fig. 2. Performance curves for some current solar collectors

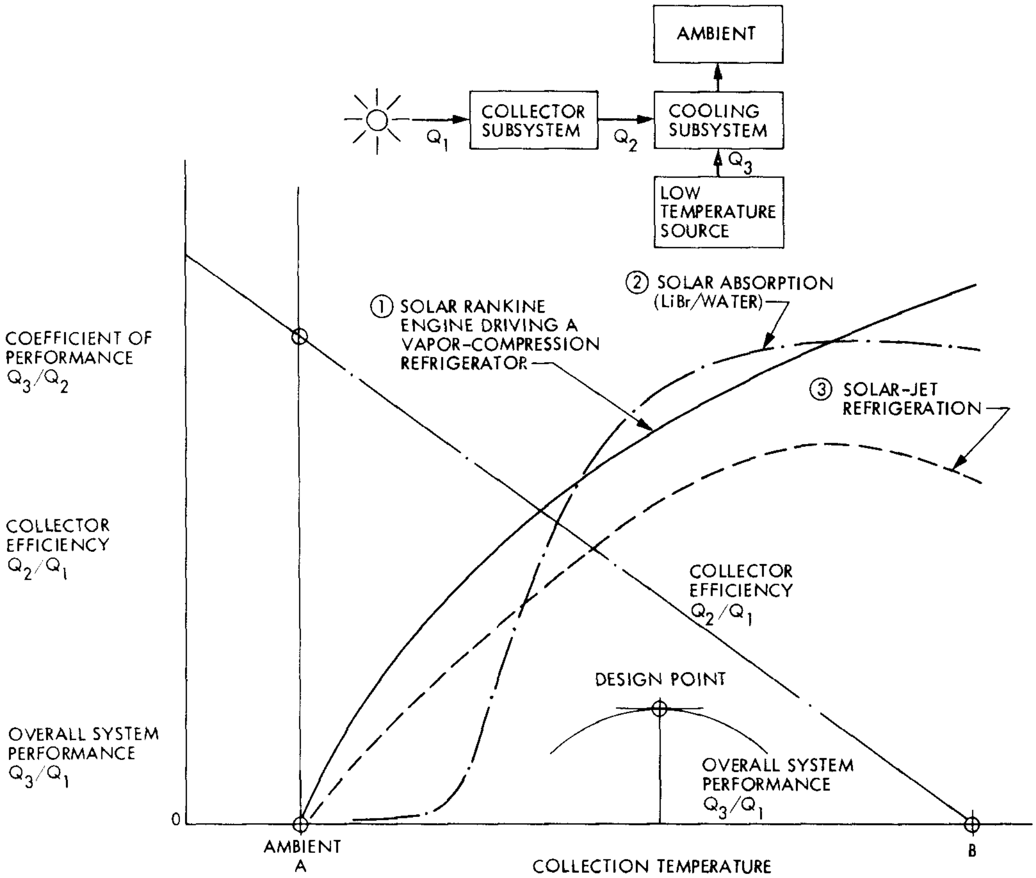

Fig. 3. Optimization of solar-thermal cooling systems